ENERGY SIGNATURES

Optimizing Production and Mitigating Impacts

Los Alamos National Laboratory's
Science of Signatures

Los Alamos
NATIONAL LABORATORY

Energy in the 21st Century

Los Alamos National Laboratory's charge is to develop science and technology that will make the Nation safer and enhance our global standing. This breadth of mission scope requires careful internal planning and effective cooperation with external partners and other governmental agencies. The document you are holding is one of the products of ongoing efforts that are designed to both help us coordinate internally and communicate externally about how the Laboratory's unique capabilities are being applied to problems of the greatest significance.

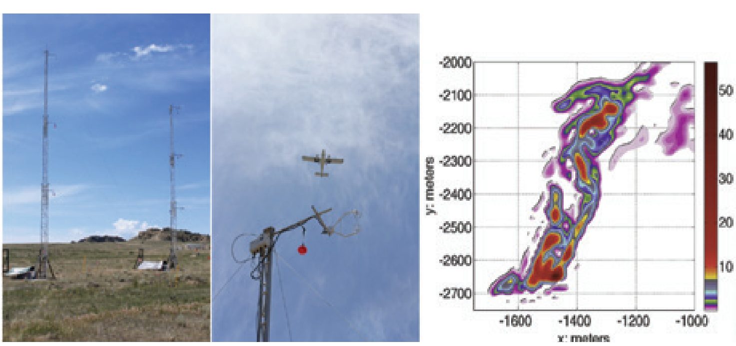
Few would dispute that energy security falls into that problem set; what is not as well known is the extent and history of the Laboratory's work in this critical area. Logically for Los Alamos, we started with nuclear when the Omega West nuclear reactor was built in the early 1950s to explore (among other things) the viability of nuclear energy. Then in the 1970s a sharp rise in awareness of the limited nature of fossil fuel reserves spurred our research into energy alternatives. A fascinating example from that time is the Hot Dry Rock project, an innovative project that used deep drilling and fracturing as a means of producing energy from geothermal sources.

Today, our research in energy spans from developing new nuclear fuels, to using supercomputers to optimize the grid, to creating new biofuels from algae, to designing materials that harvest sunlight in novel ways.

This research is motivated by strong need. The National Security Strategy, published by the White House in 2010, focuses on advancing U.S. interests in the 21st century. Energy related issues in the strategy include transforming U.S. energy use by diversifying supplies and investing in innovation, and deploying clean energy technologies to enhance energy security, create jobs, and fight climate change. Addressing these issues requires collective effort, and the Laboratory's goal is to partner effectively so that our resources are best applied to those aspects of the problem suited to our capabilities.

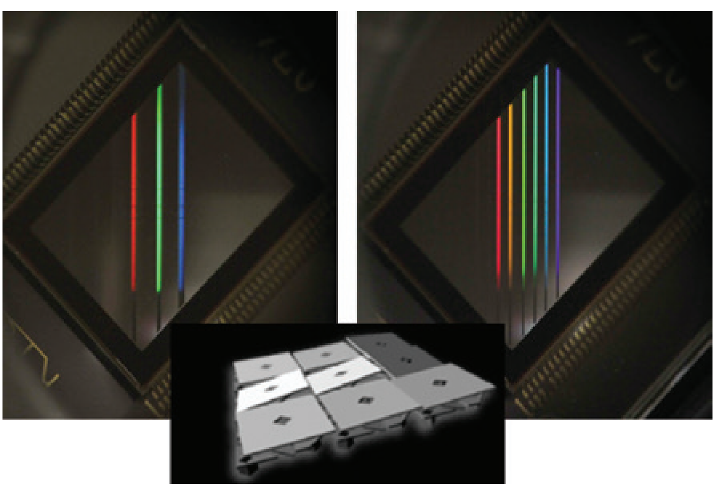
The topic of the strategy you are holding is energy signatures, an aspect of energy particularly well suited to our strengths in modeling, super-computing, and experimental science. Additional resources on the Science of Signatures (SoS) or our energy work can be requested from the contacts listed on page 20. Planning for R&D is a living process, and we welcome your feedback and questions.

Nancy Sauer is the Associate Director for Chemistry, Life, and Earth Sciences, which oversees the Science of Signatures effort for the Laboratory. She can be reached at (505) 606-2266.



Photos: a multi-scale field detection experiment involving methane release at the Rocky Mountain Oil Field Testing Facility, performed in collaboration with Chevron and Jet Propulsion Laboratory. Graph: a methane column from a LANL three dimensional atmospheric model called HIGRAD-LES.

Table of Contents



Hyperspectral imaging (HSI) is one technique under development for sensing gasses in stack plumes or industrial process outputs, including greenhouse gases. Persistent monitoring with HSI sensors enables the acquisition of enormous volumes of data, and an adaptive sensor can rapidly switch between target-specific filters for real-time monitoring of several species. Shown here is a switching apparatus.

The National Landscape

Energy security is an increasingly significant national imperative that is driven by a wide range of energy-related needs. The Laboratory's role is to understand those needs as articulated in national policy documents and to provide science-based solutions within the context of the Laboratory mission. Signature science is key to many aspects of energy security.

According to the **President's National Security Strategy (2010)**, these needs range from transforming U.S. energy use by diversifying supplies, investing in innovation, and deploying clean energy technologies to enhance energy security, create jobs, and fight climate change. It states that the U.S. must transform the energy economy, leverage private capital to accelerate deployment of clean energy technologies that cut greenhouse gas emissions, improve energy efficiency, increase use of renewable and nuclear power, reduce the dependence of vehicles on oil, and diversify energy sources and suppliers due to climate change concerns. This "all-of-the-above" strategy is reflected and amplified in other documents produced by the U.S. government, including but not limited to the following.

The President's Climate Action Plan (June 2013), which has three key objectives; 1) cut carbon pollution in America, 2) prepare the United States for the impacts of climate change, 3) lead international efforts to combat energy-productivity induced global climate change and prepare for its impacts.

The OSTP/DOE QER Quadrennial Energy Review Report (2013)**,** which is intended to identify the threats, risks, and opportunities for U.S. energy and climate security.

National Science and Technology Council – The National Global Change Research Plan 2012-2021, which is charged with developing a "comprehensive and integrated United States research program to assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

The DOE/BER/CESD Strategic Plan (2012), which calls for a robust predictive understanding of Earth's climate and environmental systems and informs the development of sustainable solutions to the nation's energy and environmental challenges. The DOE mission is to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

DHS Climate Change Adaptation Roadmap (2012), which states that energy and climate change are key issues that shape the future security environment.

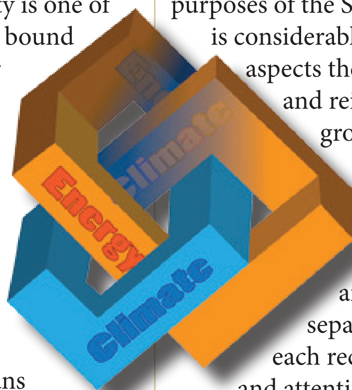
The DoD Quadrennial Defense Review (2014), which stresses the need to develop alternative energy sources and approaches for military applications and national security.

The picture that emerges from the large set of planning documents is that the concern for realistic solutions permeates every sector of government planning. Participation extends from conservation and efficiency initiatives to R&D to develop new paradigms of energy production and use. Energy signatures are a key means of minimizing energy impacts and maximizing energy productivity within the U.S. energy economy.

The importance of energy research and energy signatures is formally recognized at every level of the government.

Laboratory Planning

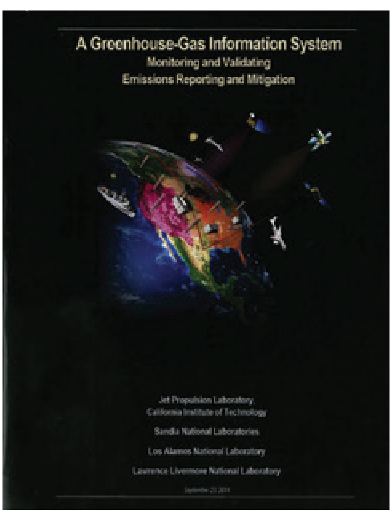
The Laboratory's mission is to serve the Nation by solving national security challenges through scientific excellence. Energy security is one of the four major mission drivers that bound our scope, and thus it is core to our work.



We work to achieve our mission in energy by providing information and science-based solutions to policy makers and national agencies. Because efforts in energy touch upon many aspects of Laboratory work, there are other Institutional and organizational plans that impact our strategic planning in Energy Signatures. Many of these integrate climate and energy themes, particularly in the arena of energy-production induced climate change, and each of them has a strong signatures component.

- **LANL Energy Security Strategy Refresh (2014).**
- **SoS Climate Impacts Plan (2013).**
- **LANL Energy and Climate Impacts (ECI). Strategic Plan (2010, Energy Security Office).**
- **Greenhouse-gas Information System (GHGIS) Study (2010/interagency).**

These plans help the Laboratory focus on energy-related R&D. Collectively their intent is to coordinate and marshal people, equipment, and facilities behind important technological problems within the scope of our mission.



The GHGIS interagency study was published in 2010.

Energy vs. Climate

The Laboratory has chosen to separate energy signatures from climate signatures for the purposes of the Science of Signatures. There is considerable overlap, and in many aspects the two topics do co-evolve and reinforce each other. However, grouping the two together has the risk of overemphasizing what they have in common rather than cultivating those areas in which they are unique. By treating them separately, we can ensure that each receives full development and attention from Laboratory staff, managers, and external stakeholders.

Who Should Read This

This document was written with multiple audiences in mind.

Our staff: This document is the high level Laboratory strategy for energy signatures. It is intended to unite Laboratory scientists behind a single strategic direction and to guide the research and efforts of our staff. It will inform investments in hiring, facilities, and equipment, as well as additional planning.

Our stakeholders: It is intended as a communications document for those outside the Laboratory who have current or potential programs that might benefit from the expertise available at Los Alamos. With it, we hope to begin a dialogue that will help us understand the technological and scientific requirements of our customers and to inform them of how we might be of assistance.

Our collaborators: Energy is a cross-organizational and multidisciplinary endeavor. To be successful, we must collaborate with other science and technology organizations, energy industries, local and national governmental bodies, and through them with the civilian population that we seek ultimately to serve. This document explains what we hope to achieve and where we will require partners to succeed.

Laboratory Context

The science pillar concept is a primary tool the Laboratory uses to plan how we will accomplish current and future missions, including the energy mission that is the focus of this document. There are four science pillars: 1-Materials for the Future (Materials), 2-Integrating Information Science and Technology for Prediction (IS&T), 3-Nuclear and Particle Futures (NPF), and 4-the Science of Signatures (SoS). Each of the pillars has discrete science goals that are fundamental to building the Laboratory's future science and technology base. These pillars support each other, and interfaces among the four pillars are leveraged for the benefit of all four.

The fundamental precept of this approach is that the greatest science breakthroughs will come as we approach difficult problems in revolutionary ways. This multidisciplinary approach draws upon physicists, materials scientists, chemists, computer scientists, theoreticians, biologists, earth scientists, space scientists, engineers, mathematicians, and numerous other disciplines to solve important national security science problems. The pillars approach gives these experts a framework for working together and allows them to apply their skills across the traditional boundaries of their disciplines.

The science pillars also inform our investments in science and engineering, guide recruitment and training strategies, and serve as a framework for our partnerships with other leading research institutions and industrial partners worldwide. Energy science incorporates a wide variety of signatures and thus responsibility for some of the associated strategic planning efforts fall under the Science of Signatures. However, there is a significant R&D component to both IS&T and Materials required in energy. Laboratory planning efforts in energy have therefore included leadership from these pillars as well.

Science of Signatures

The Science of Signatures strategic plan (revised 2014) was chartered by the Principal Associate Directorate for Science, Technology, and Engineering (PADSTE) and written by a team of more than 35 managers and scientists from across the Laboratory following a two year process. Its grounding principle is that we must be able to identify and characterize challenges before we can understand them or take action to mitigate them. Signatures are the unique elements that allow us to locate threats or discern opportunities for improvement and describe them.

The Science of Signatures pillar addresses emerging challenges by developing science and technology to detect threats or identify opportunities. Our complete technological toolbox is applied to signature science from across our mission areas of global security; nuclear defense; and energy, climate, and health. Critical components are the discovery and detection of signatures to enable detailed understanding of large, complex systems.

Specifically, we characterize measures, signals, and properties in or of complex systems in order to detect or attribute change; predict systems behavior across scales in space (molecular to global) and time (near-term to geologic), and assess impacts to the system of change.

What are energy signatures?

The Science of Signatures focuses on measuring and modeling signals and properties of complicated systems, including the intricate cycle that characterizes our energy production and use. These "energy signatures" give meaningful information that can then be used in a wide variety of ways to monitor or modify the system. Energy signatures are distinct from the other types of energy science being performed at Los Alamos, such as the creation of new materials to transform sunlight into energy, or research into alternative methods of geologic fracturing to replace hydraulic fracturing. There is some conceptual overlap because tools and techniques that measure how novel photovoltaic materials perform, or that map the extent of underground fractures would be categorized as "science of signatures," however the basic distinction between "generating valuable information" and "making something" is a clear and useful one for guiding research and marks the boundary between SoS and the other pillars.

SoS Scientific Approach

Our scientific strategy is to discover new signatures, revolutionize measurement of signatures, and deploy new technologies in the field. Each of these three components has distinct characteristics.

Discover signatures: Identify signatures of chemical, biological, radiological, nuclear, and explosives threats and of climate, energy and health security impacts. In essence, signature discovery is determining those measurable phenomena that uniquely identify and characterize properties within complex environments.

Revolutionize measurements: For threat-specific signatures, develop entirely new measurement technologies, methodologies, or strategies or develop transformational advances in the current state-of-the-art. In essence, how can sensitive and specific measurements be made in entirely new ways and/or how can new phenomena (signatures) be measured?

Forward technology deployment: Make measurement technologies and methodologies practical through engineering. This includes prototyping of sensors and instruments for field deployment and systems integration of sensor networks. In essence, how do we bring science advances to the real world in a way that provides feedback into signature discovery and/or revolutionary measurement technologies?

The strategy of *Discover, Revolutionize, Deploy* is applied to the Los Alamos SoS areas of scientific leadership:

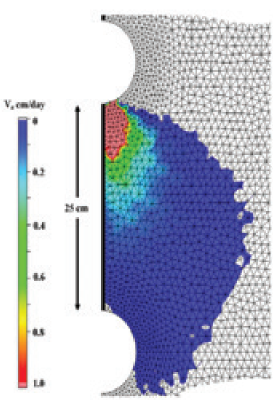
- **Nuclear and Radiological**
- **Chemical and Materials**
- **Biological**
- **Energy**
- **Climate**
- **Space**

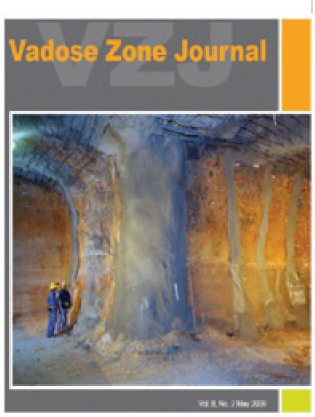
The other five areas of leadership are developing strategic plans similar to this energy plan. Each individual plan will nest with the larger SoS plan.

SoS is tightly integrated with the other pillars along the themes of Discover, Revolutionize, Deploy.

The Science of Signatures Pillar is

- **An Institutional effort led by the Associate Directorate for Chemistry, Life, and Earth Sciences.**
- **An organizing principle built on historical strengths and technical leadership.**
- **One of four science plans to shape and manage the future of science and technology at the Laboratory.**
- **Supported and mandated by DOE.**
- **Important to our immediate stakeholders and the nation.**
- **Reshaping the way we think of multidisciplinary science.**





The LANL-developed Finite Element Heat and Mass Transport (FEHM) code is the workhorse for numerous subsurface flow and transport projects for environmental management, nuclear waste repository design, carbon sequestration, unconventional fuel development, and geothermal energy. Shown at left, FEHM is used to simulate a tracer injection test at Busted Butte, NV.

Energy Overview

The Science of Signatures strongly supports LANL's energy security mission. Energy security takes the dual approach of developing transformative new energy technologies while simultaneously enhancing current technologies, and doing so in a sustainable manner that mitigates negative environmental, social, and national security impacts. Implicit in this approach is the need to develop capabilities to measure, model, and predict the impacts of energy choices on global climate, the economy, national security, and the environment and society (energy signatures).

LANL has extensive experience in signatures relevant to energy. Decades of work deploying underground nuclear tests provide a foundation for signature development and field deployment in downhole, subsurface, desert, and other extreme environments. An example is the Hot Dry Rock program that LANL pioneered from the 1970s through 1990s. This energy production experiment used geothermal sources to create energy and required complementary expertise in extreme (high temperature) signature development and field deployment.

Our vision is for the Laboratory to work across discipline-based boundaries and use our unique strengths in sustainable energy, concepts and materials for clean energy, modeling and simulation, and supercomputing to revolutionize energy science in America.

Going forward, Los Alamos' seminal contributions in seismic and radiological/nuclear signatures for nonproliferation provide experience for signature discovery in subsurface energy systems such as oil and gas, carbon sequestration sites, engineered geothermal systems, geologic repositories for nuclear waste, and for high-radiation environments, such as next-generation nuclear reactors.

LANL staff also have experience in setting up large treaty monitoring data centers useful for energy/climate treaties. The prototype for the Comprehensive Test Ban Treaty Organization data center in Vienna, Austria, was developed by LANL scientists. Finally, LANL's leadership in space- and atmosphere-based signatures for nuclear-weapons-treaty verification over the past 50 years enables a potential leadership role in Green House Gas Information System (GHGIS)-type efforts.

Energy Security Focus

There are three basic concepts that form the core of LANL's approach to energy science. Signatures are an integral part of each.

1. Sustainable nuclear energy includes innovative approaches to fission and fusion energy generation that provide effective waste management, minimized operation and nuclear proliferation risks, high efficiency fuel use, and extended reactor lifetimes. Specific areas of strength and interest:

- Optimizing existing nuclear energy infrastructure,
- Science, technology for advanced special-purpose reactors,
- Science and Technology for future nuclear energy fuel cycles,
- Solutions for global nuclear materials and waste management, and
- Modeling and simulation for accelerated nuclear energy system deployment.

2. Concepts and materials for clean energy include research that contributes to energy security and to the reduction of greenhouse gases through innovative technology or transformational enhancement of existing technologies. It emphasizes systems analysis, chemistry, bioscience, materials science, and materials integration techniques. Specific areas of strength and interest:

- Bioenergy and biomass-derived chemicals and materials,
- Advanced materials and systems for clean, efficient transportation and power applications,
- Simulations of fossil energy systems,
- Science and technology for renewing and protecting the grid,
- Optimization and design of clean energy manufacturing, and
- Science and technology for renewable energy development.

3. Measuring, predicting, and mitigating impacts of growing energy demand and use.
Integrated modeling and signatures can elucidate and predict the complex interactions of energy demand and help eliminate the negative impacts of increased energy use on climate, natural, social, and engineered systems. Specific areas of strength and interest:

- Energy/water nexus,
- Climate and energy system modeling,
- Greenhouse gas measurements,
- Uncertainty quantification, and
- Decision support.

Science Approach

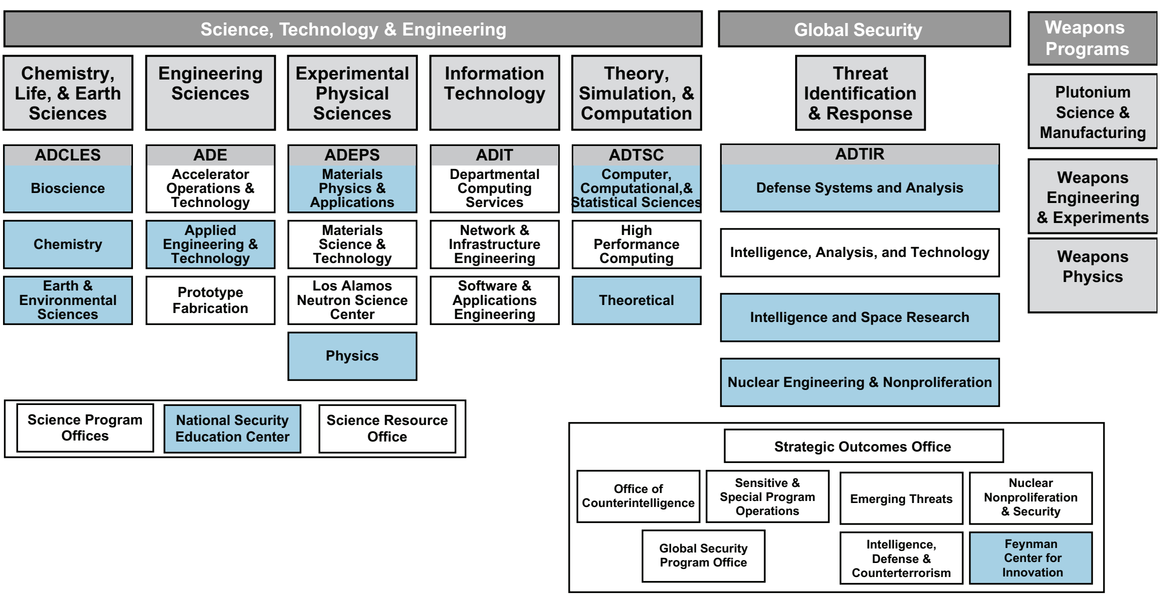
Acknowledged strengths form the core of our approach to solving problems in energy signatures.

Computation. The computer and computational sciences capability resident at Los Alamos is unparalleled and provides a foundational contribution to developing solutions in energy signatures.

Modeling and Simulation. Similarly, LANL's modeling and simulation capabilities are critical to our energy signatures strategy. Integrated climate and energy science computational needs require "exascale" capabilities and visualization, which the Laboratory maintains as part of our computational capability. The modeling and simulation aspects of these challenges include contributions in the following areas:

- Infrastructure modeling, design, and optimization,
- Uncertainty quantification (UQ) for global and regional scale prediction, and
- Quantification of GHG emissions and offsets for policy makers and scientists.

Observational and Experimental Data Acquisition - Energy Test-beds.
Los Alamos is internationally known for fielding complex experiments and for observational capabilities and technology. We have unique observational capabilities across a wide range of multidisciplinary measurement capabilities that often define new levels of performance. Examples include compact instruments for remote sensing systems and sensitivity for measuring signals that are very weak (such as the signatures of solar neutrinos and of magnetic fields in the human brain), very large (such as the outputs from explosions and pulsed electrical discharges), or very fast (such as sub-picosecond studies of chemical dynamic and ultra-fast-laser experiments).



Laboratory organizational chart showing in blue the principal organizations that currently contribute to energy signatures science development. The Laboratory as a whole has a budget of over $2 billion and more than 9000 employees, and while our "bench strength" is already great, it can clearly go much deeper should the science challenges demand it.

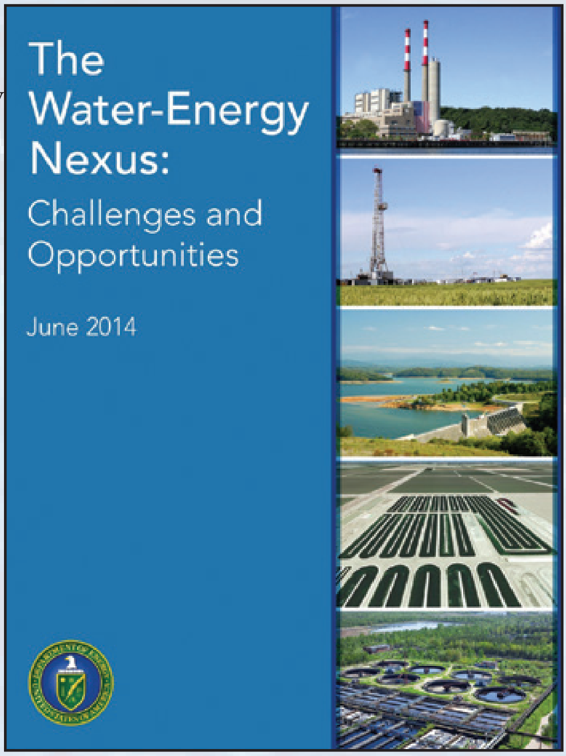
The Energy-Water Nexus: An SoS Challenge

Energy and water are inextricably intertwined. On one side of the equation, energy is required to pump water out of the ground, purify it in a variety of ways, move it through distribution systems, moderate its temperature during use, and more. Following use, energy is needed to treat waste water before it is returned to the environment. On the other side of the equation, water is required to produce energy. It is used to cool power plants, in hydraulic fracturing to extract oil from the ground, and to produce alternatives such as biodiesel and ethanol.

> "Because energy and water are interdependent, the availability and predictability of water resources can directly affect energy systems. We cannot assume the future is like the past in terms of climate, technology, and the evolving decision landscape."
>
> -Ernest Moniz, DOE Secretary

The crux of the energy/water nexus arises because the supply of both water and energy is decreasing while the demand rises globally. In fact, issues of water scarcity, variability, and uncertainty are cropping up more frequently each year, highlighting vulnerabilities in our current modes of use. Examples from recent years include power plants that either could not operate or that operated at reduced capacity due to severe droughts, and the effects of natural disasters such as Superstorm Sandy on both water and energy delivery systems.

The significance to our national security is clear, and there are social, political, and scientific aspects that must be grappled with in planning for amelioration. Numerous federal agencies have roles to play, including the U.S. Department of Energy, whose role lies largely in supplying science and technology drawn from the national laboratories. The DOE strategy was outlined in the detailed Water-Energy Nexus report released in June, 2014.

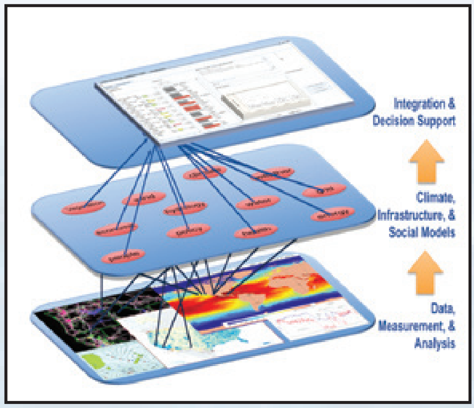


In June of 2014, the DOE and partners released this 260 page report, which outlines a strategy for approaching the energy-water nexus problem. LANL staff participated in the preparation of the report, and the Lab aligns with the principles it outlines.

Within the context of the Science of Signatures, the Laboratory's role is to furnish high-confidence information and recommendations to decision making bodies and funding agencies. To make progress towards solutions, those customers will inevitably require help with prioritization and input on increasing efficiency of water use, topics requiring innovative scientific solutions. The Laboratory and its partners can provide those solutions.

Data Modeling and Analysis

One of the unique aspects of the Laboratory is our ability to combine the most advanced supercomputing facilities in the World with modeling and simulation expertise in energy-related topics. Modeling of water-energy nexus issues requires computing power and modeling expertise on that scale, because simulating how engineered and natural systems interact is a hugely complex challenge. The aspects that must be considered include not only water and energy interactions, but also population models, human migration patterns, socioeconomic factors, and more. By working with partners, the Laboratory hopes to be able to assist policy makers by providing decision support tools.



Smaller scale examples of applied modeling and simulation apply over a wide range of scales and include grid analysis and optimization, grid decision-making tools, and the quantification of needs for energy use and storage.

Technology Deployment
Creating deployable signature-related technologies is another Laboratory goal that applies directly to the energy-water nexus. These might include development of tools and techniques for testing and evaluation of all aspects of the energy-water equation, systems integration, and field-based technologies for monitoring and evaluation.

Related technology development challenges include design and control of microstructures for advanced fuels (both nuclear and non-nuclear) and structural materials, and the characterization of new waste forms. Along with these go new approaches to safeguards instrumentation, fundamental nuclear data for advanced fuels, and much more.

Energy and water are codependent systems that are vital to our health and prosperity. Managing their delicate symbiosis requires a profound scientific understanding of how they affect each other and the environment.

Case Study: Multiphase Metering for Oil and Gas Reservoirs SFAI/Safire 2.0 Meter

As the oil and gas industry moves into the 21st century, it needs to produce from "smart" oil fields. Current practices use devices such as separators and Coriolis meters to track production from well fields; sampling is cumbersome, costly, has potential negative environmental consequences (leaks), and typically occurs infrequently (every 4-6 weeks). Sampling methods have not changed significantly in the past 50 years, and the sampling frequency does not effectively optimize production.

The Laboratory has partnered with Chevron and GE Oil & Gas to develop the Safire 2.0 multiphase-flow meter. This technology, which is largely based on the swept-frequency acoustic interferometry (SFAI) technique, has its roots in LANL global security programs. Early applications of SFAI focused on detecting chemical agents in closed containers based on their acoustic properties. SFAI uses sound over a wide frequency range to characterize liquids, gasses, mixtures, emulsions, and other fluids inside pipes and containers. The propagation of such wideband ultrasonic frequencies in the form of a short-duration frequency chirp through a multiphase medium is analyzed to extract frequency-dependent physical properties of that medium.

A Safire 2.0 multiphase flow meter.

The propagation time and attenuation of the chirp signal as a function of frequency are analyzed to extract both fluid flow and multiphase fluid composition information. Key innovations for the Safire 2.0 flow meter include advanced data-processing algorithms, sophisticated electronics, and effective temperature compensation. The technology has been tested in field trials in Chevron's San Joaquin Valley operations. The real-time, continuous SFAI data usually agree within < 1 % with data collected using periodic manual testing methods. In 2014, the Safire multiphase meter was recognized with a prestigious R&D 100 award.

The Safire 2.0 flow meter accurately measures oil flow rate and water cut (the percent of water within the mixed-phase product stream) in the presence of gas flowing in topside piping. Measurements can be made at an individual well with a rate of better than once per second. Measurements are non-invasive, being accomplished using transducers and other hardware on the outside of the piping. Safire meters are also relatively inexpensive, so they can be widely used in oil and gas fields.

Knowing the oil/water cut and flow rates in real time allows greatly enhanced optimization of oilfield production because production parameters such as pump rates or steam flood frequencies can be continually adjusted. Well-specific data also allow improved modeling of well-to-well interactions. Non-productive wells can be rapidly identified, taken off-line, and maintained to improve overall production. The ultimate goal is to increase production and recovery up to 10%, which benefits both the oil and gas industry and the U.S. economy. Additional benefits of the Safire 2.0 meter include less environmental risk due to elimination of the need to collect samples using separation tanks or other intrusive sampling devices; a reduction in the number or joints that can leak liquids or hydrocarbons; lower costs and reduced maintenance; remote, automated analysis; and a decrease in the footprint of infrastructure at individual wellheads.

Future generations of SFAI-based meters are anticipated to be able to provide complete gas/water/oil/sand compositions, along with flow rates, and will ultimately be deployable in downhole environments. A challenge to the industry will be digesting the vast data streams derived from hundreds or thousands of these flowmeters and integrating them with process-control systems for producing oil and gas fields. This is a Science of Signatures "big data" problem for the future.

A suite of Safire 2.0 multiphase meters deployed in an oil field setting.

Goal 1: Signature Extraction

In pursuit of this goal, we seek to pioneer new ways to extract and attribute energy signatures in living, geological, man-made, and other systems under conditions that are remote, inaccessible, or otherwise challenging.

“Signature discovery” in this wide range of systems includes identifying characteristic signals in upstream energy extraction, downstream energy production, and waste management activities across multiple energy sectors such as fossil fuels, next-generation nuclear, geothermal, and other renewables.

All of these sectors are expanding their operational envelopes. Oil and gas drilling is being pursued at depths and temperatures previously not attempted, power generation plants are striving to improve efficiencies by operating in new regimes (e.g. pressurized fluidized bed combustion), carbon associated with fossil fuel combustion may need to be monitored across atmospheric scales from local to global, and nuclear waste repositories are being proposed for new geologic environments (e.g. salt deposits), where new science and technology problems exist.

These challenging environments require new signatures gathered from both innovative hardware and integrated data extraction methodologies. With these new signatures, industry will be better poised to optimize resource extraction, maximize energy production, and control waste management activities.

Cracks and other defects buried within a translucent cube can be detected using a signature technique called “time reversal.” The time reversal technique can be used for nondestructive evaluation and sensing in a wide range of energy applications including oil and gas, geothermal, and nuclear waste repositories.

Los Alamos is poised to develop such new signatures at scales from micro to regional through integration of computational methods, novel laboratory science and engineering, and advanced field deployment. These new signatures will help the Nation meet goals to provide sustainable, clean, American-made energy to foster our economic vitality.

Objective 1.1: Signature Discovery - Energy Systems

Signature science has much to offer to the energy sectors of oil and gas, clean coal, nuclear energy, engineered geothermal systems (EGS), biofuels, solar power, and others. Some of these sectors are central to the Laboratory’s mission, such as nuclear energy, while others represent key national priority areas where unique Laboratory technologies can solve energy security problems while developing capabilities vital for other core missions. Signatures are important in upstream environments (energy exploration and production), downstream facilities (energy-product formulation), small-scale energy subsystems (e.g. battery or fuel cell performance), and energy-relevant waste management environments (e.g. nuclear waste repositories).

Objective 1.2: Signature Detection - Mechanistic Understanding

Along with new energy signature discovery tools (see Objective 1.1 above), LANL research seeks an improved mechanistic understanding of energy signatures and of their development and extraction. These signatures might be within and amongst molecules, or they might be global in nature and found in the ocean, air, and land. A mechanistic understanding of energy signatures should enable the development of additional signatures and more effective deployment of signature tools. These tools can in turn identify damage precursors and potential failure modes in energy systems, evaluate environmental and infrastructure consequences of energy systems (including ecological impacts), and ultimately optimize operation of a range of energy systems. A key aspect of such efforts is integrating with the Information Science and Technology (IS&T) pillar to develop predictive models and decision support tools that describe signature/energy system/infrastructure interactions, which can be used to optimize energy system processes and to validate energy-signature-based inferences concerning energy systems. Improved design principles for energy systems will be realized as engineering practice moves from empirical and Edisonian to knowledge-based.

Objective 1.3: Full-scale Deployment of Energy-sensing Systems

Ultimately, energy-signature diagnostic systems need to be deployed at pilot- or full-scale in the environment or in the energy-production (utility) sector. LANL-developed technologies need to be prototyped and deployed in the field for both government customers and for the industrial sector.

Historically, LANL has been perceived as more focused on early-stage science and technology; however, we have a long history of field deployment of sensors in the nuclear testing program. In energy systems, field-scale systems such as the Hot Dry Rock project at Fenton Hill required extensive down hole chemical diagnostics and micro-seismic monitoring of fracture development. The Laboratory has deployed a range of field-scale tests in support of repository science (Yucca Mountain tests such as Busted Butte), the DOE ARM program, carbon sequestration regional partnerships, and at Macondo/Deepwater Horizon.

Hot dry rock/engineered geothermal systems - Fenton Hill, New Mexico deployment.

Los Alamos is partnering with Toshiba Corporation to use a Los Alamos technique called muon tomography to safely peer inside the cores of the Fukushima Daiichi reactors and create high-resolution images of the damaged nuclear material inside without ever breaching the cores themselves.

Right: Remote verification measurements of fossil fuel power plant emissions in New Mexico's 4 Corners region.

"Multi-scale Observations of CO_2, $13CO_2$ and Pollutants at Four Corners for Emission Verification and Attribution," Proceedings of the National Academy of Sciences 13, 21883 (2014) doi:10.1073/pnas.1321883111

Goal 2: Materials for Sensors and Sensing Systems

This goal focuses on developing materials for sensors that facilitate the production, transmission, and utilization of energy. These novel sensors may include new materials that will be used to monitor energy systems. Energy systems, as defined in Goal 1, include upstream energy extraction, downstream energy production, and waste management activities across multiple energy sectors (fossil fuels, next-generation nuclear, geothermal, and renewables such as the production of fuels from biomass).

As these new energy sources continue to expand their operational parameters to more and more challenging environments, new sensors and sensor materials will be needed to monitor production efficiency, performance in real time, and the condition of the materials (e.g. pipes, cables, etc.) that are used in the process.

Oil and gas drilling is being pursued at depths and temperatures previously not attempted, power generation plants are striving to improve efficiencies by operating in new regimes (e.g. pressurized fluidized bed combustion), carbon associated with fossil fuel combustion needs to be monitored across atmospheric scales from local to global, and nuclear waste repositories are being proposed for new geologic environments (e.g. salt). In each of these cases, new materials science problems exist because of the unusual environmental conditions that will be encountered. These challenging new environments may require completely new sensors to acquire and process the signatures.

Los Alamos will develop new sensor materials and sensor systems as a consequence of research that is being performed under the Materials pillar. The Laboratory has experience with the behavior of materials in extreme environments and the pursuit of Goal 2 is enabled by expertise in this area. The challenging environments of new energy technologies provide opportunities to showcase new materials for sensor technology when established materials fail simply because they cannot withstand the environment being probed. Development of such novel sensors will help meet national goals to provide sustainable, clean, American-made energy sources that will sustain our economic vitality.

Objective 2.1: Develop Materials and Sensors for Fossil Energy Applications

Fossil energy sources will continue to be our largest energy production resource for the indefinite future. The recent boom in natural gas discovery through high resolution seismic imaging and recovery through directional drilling and hydraulic fracturing technologies demonstrates the sheer quantity of material that has become accessible via these new technologies, with recent estimates suggesting U.S. energy independence by 2020 or even sooner.

Exploration and production from deeper water formations as well as from other more challenging environments will continue as more resources are discovered. As these processes are used for the recovery of fossil energy resources, novel sensors that can be used to improve extraction, to monitor the status of production, and to diagnose the health of infrastructure will be necessary to ensure maximizing recovery as well as to prevent leaks and ensure the health of the environment. Monitoring the condition of the materials that are used in real time will also become even more important given the harsh conditions that will be encountered on a routine basis.

Objective 2.2: Develop Materials and Sensors for Nuclear Energy Applications

A key goal within the nuclear energy, nuclear weapons, and nuclear non-proliferation arenas is developing materials, including sensor materials, with strong radiation resistance. Many sensor materials in high radiation environments break down rapidly, presenting a unique materials problem in which LANL has world-class expertise. As reactor designs change, the spectrum of radiation within such reactors may also change, necessitating sensor materials development. Another sensor materials problem related to the nuclear fuel cycle would be design of new sensor materials that are robust within the high-salt/salinity environment of a potential salt repository.

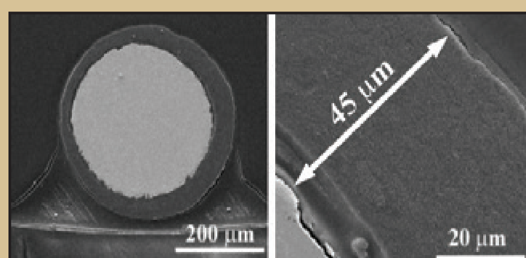
Objective 2.3: Develop Materials and Sensors for Renewable Energy Applications

Despite the recent increase in access to fossil fuels from new exploration and recovery technologies, increasing levels of atmospheric carbon dioxide with attendant concerns about climate change have driven investment in renewable sources of energy. The significant investments that have been made in wind, solar photovoltaic, engineered geothermal systems, and biofuel production suggests that these technologies are here to stay and will continue to develop and evolve as energy needs increase with increasing population. It is clear that energy production from renewables will continue to grow.

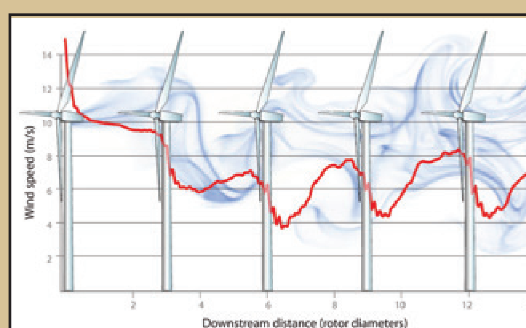
Renewable energy sources will have different signatures associated with production and possibly use than those associated with fossil fuels. Even a process that is generally similar to petroleum refining, such as biofuel production and refining, will have significantly different parameters and materials needs. This is because the chemical composition of biofuel feedstocks is very different from conventional petroleum feeds, which results in different requirements for piping and reactor materials.

Similar to oil and gas, new engineered geothermal systems are being designed for higher temperature conditions, requiring sensor materials that operate at these extremes. Thus, there is a need for signature discovery (as outlined in Goal 1) as well as for the development of sensors that are specific to the needs of renewable energy resources.

Scientists have developed a ground-breaking, high temperature, sulfur resistant electrode for oxygen sensors that increases their life, stability, and accuracy. This patented electrode, Terbium-Yttrium-zirconium oxide (Tb-YSZ), is resistant to sulfur and other acidic compounds present in exhaust gases that destroy O_2 sensors on the market today.



This LANL-developed novel and lightweight conductor has a demonstrated specific conductivity (σ) that may ultimately exceed that of copper. It uses composite wire comprised of two electrically active parts: a copper core and a carbon nanotube coating.



Five simulated turbines in a row, spaced three turbine diameters apart, produce a rapid loss of incoming wind speed that eventually lead to about half of the initial wind speed reaching the turbines in back.

Goal 3: Decision Support

This goal focuses on the challenge of integrating measurements, models, and data for the complex systems that characterize energy infrastructure (production, transmission, and distribution) and energy use. Understanding based on science and technology can support decisions and investments, protect systems and anticipate risks/degradation, and respond to disruptions, impacts, and consequences. We face the threat of climate change impacts, energy related national security threats, and an outdated energy infrastructure.

Understanding, predicting, and mitigating impacts can lead to a reliable supply of energy. Achieving energy security in today's global environment requires the U.S. to make policy decisions based on the best data and analyses, and LANL can help. Some areas where decision tools can aid in understanding follow:

- Energy production decisions related to hydro, nuclear, coal, gas, solar, wind, and biofuel use,
- Energy system design and security, including transmission/distribution, grid cybersecurity, and interdependencies associated with interconnected infrastructure (electrical grid, natural gas and water) and production processes,
- Understanding reservoirs/repositories for energy products and by-products such as nuclear waste, CO_2, natural gas, geothermal, and water resources,
- Ecological impacts associated with climate change, water, agriculture needs, and extreme events,
- Economic decisions: optimal utilization of energy vs. water; optimal mix of energy delivery/production,
- Social impacts due to water consumption vs. energy production; emissions impacts on health, security, food resource; energy transmission costs to consumers; energy costs, and
- Politically related challenges: greenhouse gas climate impact verification and international emission limits.

Decision makers need decision and assessment tools to quantify risk, understand impacts, predict consequences, and ultimately make optimum choices.

Objective 3.1: Signature Discovery and Prediction – Energy and Infrastructure Systems

In addition to developing advanced tools and techniques for data analysis discovery and prediction of energy signatures, LANL research focuses on developing an enhanced understanding and correlation of energy signatures to identify and discriminate degradation, failure and capacity of energy and infrastructure systems in a manner that quantifies uncertainty. An example would be for greenhouse gas (GHG) capture/storage systems. LANL is also pursuing research into decision support for integrated modeling of climate/environmental (natural) and engineered (human) systems; identifying change in signatures for climate/environmental systems; and quantifying uncertainty (risk) results of this integrated predictive modeling.

The growth in global energy demand will put increasing pressure on climate, the environment, and infrastructure/engineered systems. Most global energy demand will be met through the expansion of fossil fuel use over the next fifteen years, which will result in a significant increase in GHG emissions. These increased GHG emissions could accelerate climate change impacts, including ice sheet and sea ice melting, sea level rise, increasing frequency of extreme weather events, infrastructure degradation and failure, prolonged drought, famine, spread of disease, migration, and social conflict. A critical national security driver is to understand the consequence of these impacts and outcomes, including predicting the degradation and failure of infrastructure. Prediction will enable understanding and allow adaptation and mitigation of the possible negative impacts of increased energy consumption.

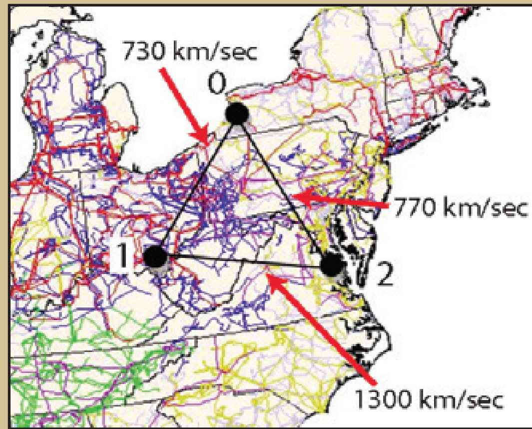
Objective 3.2: Signature Detection Across Scales

This objective intends to develop and deploy advanced (e.g., high-fidelity/low-cost) sensors to monitor spatial and temporal changes related to engineered systems and climate impacts. It also develops remote sensing platforms (air and space) with in-situ signature collection, and then integrate, correlate, interpret, and identify natural or engineered system damage or change.

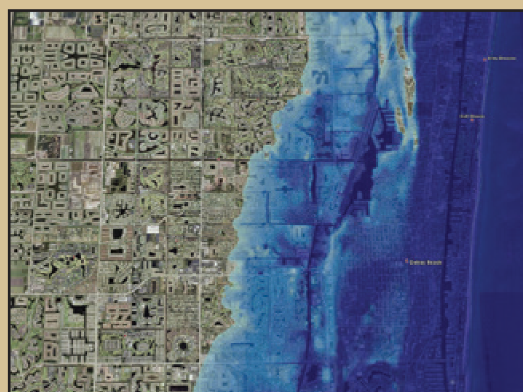
A unique LANL strength is our capability to combine measurements or observations (local, regional, and global), computational models, and expert judgment to make inferences about change on the regional and national scale. This capability connects models and data at different resolutions using measurements/ observations to constrain components of various computational models and then to assesses and validate regional climate models. This method has a strong dependence on uncertainty quantification (UQ), another area of LANL expertise. We have been working in the UQ area, making inferences with the aid of computational models in applications that include nuclear weapon assessment, engineering, physics and hydrology. LANL has also applied remote sensing data fusion techniques to detect and quantify climate change impacts on vegetation, permafrost, hydrology and landscape dynamics. We have an opportunity to leverage this unique expertise to further develop and deploy sensors to monitor temporal and spatial changes in the environment and atmospheric emissions of carbon, interpret signals, and identify change and damage of direct benefit to energy security.

Objective 3.3: Integrated Modeling, Assessment Decision Tools, and Monitoring Technology

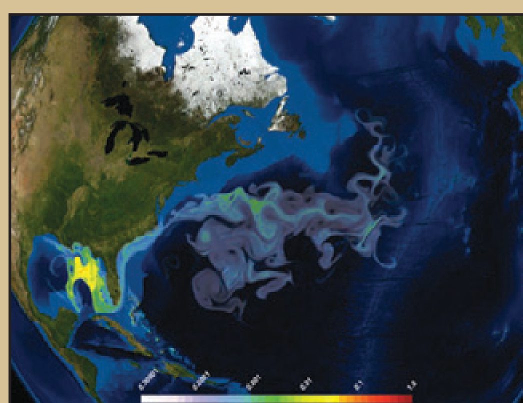
This objective expands application and development of integrated modeling, assessment decision tools, and monitoring technology to predict and mitigate impacts and threats to natural and engineered systems and then plan responses. It includes databases (or knowledge-bases) and algorithms for real-time analysis of large volumes of diverse monitoring data. It applies an uncertainty quantification framework (data model, system model, and decision model) for regional, national, and international analysis of impacts and outcomes to human, socioeconomic and technical, and natural systems across a range of temporal and spatial scales.



Using signal processing techniques developed for imaging in seismology, LANL has demonstrated a technique for monitoring and predicting the propagation of grid disturbances and assessing stability.



Based upon surge (storm characteristics/strength/ intensity) and other constraints, computer models can predict damage to infrastructure and population.



Modeling the Deepwater Horizon oil spill: The dispersion and dilution of a virtual dye 180 days after the initial spill. The color scale shows the dilution factor, the ratio of total amount of dye in the water column to the amount injected at the source. http://www.lanl.gov/science/1663/march2011/story6.shtml

First printing, 2015.

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Los Alamos National Security, LLC, for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396.

A U.S. Department of Energy Laboratory LA-UR-14-29191

The Laboratory collaborates with both government and industry in SoS energy. We welcome new partnerships, and we are constantly seeking to expand the scope of our work, both internally and externally.

Should you wish more information on the various aspects of the work described in this document, please contact us. The Science of Signatures is overseen by the Chemistry, Life, and Earth Science Directorate Office.

Chemistry, Life, and Earth Sciences
Phone: (505) 606-2266
Mail Stop: F629
Los Alamos National Laboratory, 87545

Los Alamos NATIONAL LABORATORY

National Nuclear Security Administration